OPERATIONS AUTOMATION USING THE LINK MONITOR & CONTROL OPERATOR ASSISTANT

Lorrine F. Lee
Lynne P. Cooper

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109

Abstract

The Link Monitor & Control Operator Assistant (LMC OA) is a knowledge-based prototype system which uses Artificial Intelligence (AI) techniques to provide semi-automated monitor and control functions to support operations of the Deep Space Network (DSN) 70-Meter antenna at the Goldstone Deep Space Communications Complex (DSCC). The manual and time-consuming process of configuring the 70-Meter antenna and its associated communications and processing equipment, known as precalibration, is an overhead activity; the time spent in precalibration is time which cannot be spent supporting actual mission operations. Therefore, the major goal of the LMC OA task is to demonstrate techniques that reduce precalibration time, decrease operations overhead, and increase the availability of this valuable and oversubscribed NASA resource. The LMC OA prototype was tested in a parallel, experimental mode at the Goldstone DSCC performing semi-automated precalibration using the actual operational equipment. This test demonstrated that a reduction of 40% in precalibration time can be achieved with the LMC OA prototype.

Introduction

The Jet Propulsion Laboratory manages a world-wide network of antennas, the Deep Space Network (DSN), which is responsible for providing the communications link with a spacecraft. Operations personnel are responsible for creating and maintaining the communications link by configuring the required subsystems and performing test and calibration procedures. This task of creating the communications link, known as precalibration, is a manual and time-consuming process which requires operator input of over a hundred control directives and operator monitoring of over a thousand event messages and several dozen displays to determine the execution status of the system. The existing Link Monitor and Control (LMC) system requires the operator to perform a large amount of textual keyboard entries, to monitor and interpret a large number of messages to determine the state of the system and to selectively cull out relevant information from dozens of pre-defined, data-intensive displays. This results in an environment in which it is difficult to operate efficiently.

The goal of the Link Monitor and Control Operator Assistant (LMC OA) task is to demonstrate automated operations techniques which will improve operations efficiency and reduce precalibration time. The LMC OA is a knowledge-based prototype system which incorporates Artificial Intelligence (AI) technology to provide semi-automated monitor and control functions to support operating the DSN 70-Meter antenna at the Goldstone Deep Space Communications Complex (DSCC). Improved operations is achieved by using a flexible and powerful procedural representation, by reducing the amount of operator keyboard entries and by providing explicit closed loop communications and control through an expert system module.

The precalibration process for Very Long Baseline Interferometry (VLBI) on the 70-Meter antenna was selected as the test domain for the prototype. The LMC OA was field tested at the Goldstone DSCC by performing a semi-automated precalibration for VLBI using actual operational equipment. The test demonstrated that a reduction of 40% in precalibration time can be achieved with the LMC OA prototype.

The 1 .MC OA has three major components: the Temporal Dependency Network (TDN), the Execution Manager (I{ M), and the Situation Manager (SM). These three components work together to provide a closed loop, system level control system for precalibration. The TDN is a directed network that allows representation of parallel procedural paths, precedence relations, preconditions and postconditions. It is the primary knowledge base for the system. The EM is responsible for traversing the TDN and sending control directives to the subsystems while maintaining the precedence, parallel and sequential constraints specified in the "1'1)N. "1 he SM works in step with the EM to provide the situational awareness necessary to close the control loop, to detect anomalies and to support recovery from anomalies. The SM maintains an internal model of the expected and actual states of the subsystems in order to determine if each control directive executed successfully and to provide feedback to the user.

The next section describes the problems identified with the existing 1 .MC system. The following sections will cover the approach taken by the LMC OA in addressing the identified problems. The two major concepts which drove the 1 .MC OA design will be presented. "l'his will be followed by a description of the TDN, which is our primary knowledge representation. A detailed discussion of the three major modules and an operational scenario will be presented. 1 n conclusion, the results of operational field testing will be discussed.

Problem Description

Currently, for standard operations, an operator is allocated 45 minutes to perform a precalibration. In the case of more complex operations such as VLBI, an operator may be allocated much more. l'recalibration is a time consuming process because of limitations in the existing operational monitor and control system. It is a command-line, keyboard-entry system that requires operators to manually send hundreds of directives to subsystems and monitor over a thousand incoming messages on a text-based scrolling log. The system lacks explicit, informative responses about the state of a directive and does not provide Guaranteed communications between the monitor and control system and subsystems being controlled. For each directive sent by the operator, the subsystem usually returns a *directive response* which is simply an acknowledgment from the subsystem informing the operator whether the directive was received or rejected. A directive response does not indicate the successful or unsuccessful execution of a directive. The subsystem may also send out *event notice messages*, which relay information about the state of some device in a subsystem. However, these messages are not explicitly tied to any directive that was sent. The operator must rely on his experience to determine which directive was most likely to have caused the subsystem to send the event notice message. *Monitor data*, which are sent periodically by the subsystems, also provide information about device states. However, monitor data are never displayed automatically or tied to any directive. instead, a subset of monitor data are formatted into pre-defined displays that the operator can invoke. The operator has to decide which piece of the data he's interested in and which display contains that piece of information. Often times, a display will contain many pieces of information of which the operator only needs one or two.

The inability of the monitor and control system to keep up with input from the subsystems causes messages to be dropped at monitor and control. To compound the problem, the subsystems cannot detect when a message has been dropped and thus cannot resend information. This situation causes false alarms which can inundate the user and often hides real alarm situations. Finally, the system is prone to input errors. A simple precalibration pass requires over a hundred directives to be issued. The operator must manually identify and type each directive and its parameters. A subsystem can take several minutes to recover from a simple typographic error.

The operator uses a variety of support data such as schedules, predict files, sequence of events and pass briefings to determine the type of pass, the spacecraft being track-d and how to configure the communications and processing equipment. information contained in the support data files is also used to determine the correct parameters for the control directives.

Because these files are not available electronically for easy viewing and usage, the operator must refer to the hard copy version of these files and manually enter numerical parameters for control directives where the numbers often times are accurate to 10 decimal places. An entry error in any of the digits could cause a major problem in the system.

The most difficult part of precalibration is the determination, by the operator, of what directives need to be sent and how the directives should be ordered. Currently, there does not exist any end-to-end representation of operations procedures. The documentation that does exist addresses a specific subsystem or spacecraft, or provides a general overview of an activity. The operators must, based on their own experience, assemble an end-to-end operational sequence. Thus the operational sequences vary from operator to operator leading to inconsistencies in operations and making recovery from anomalies d ifficult.

In summary, the following are the specific operability problems identified with the existing LMC.

1. Extensive manual entry is required of the operator.

2. The lack of integrated monitoring tools for the operator makes it difficult or nearly impossible to perform parallel operations. The operator must mentally interpret displays and text messages to determine correct execu tion of a directive.

3. False alarms due to dropped messages occur frequently. Dropped messages are not detected and retransmitted by the subsystem, which results in the operator having an incomplete picture Of the system state.

4. The lack of on-line access to usable support data increases the need to integrate information from multiple sources, Entry of complex numerical parameters increases the chances of typographical errors.

5. There is no end-to-end representation of the operations procedures.

Closed 100p Control and Situational Awareness

There are two major design concepts in the LMC OA. The first is closed loop control and the second is situational awareness. In the LMC OA context, closed loop control means that all control actions (i.e., directives) have explicit feedback regarding the success or failure of the requested action. Under the existing monitor and control system, there is no single message that reports the status of a d irective. Rather, in the existing system, the operator must sift through many different data messages returned by the subsystems and many d ifferent displays to determine the status of the directive. Unfortuna tel y, this process of filtering for and identifying pertinent data is time-consuming. The LMC 0A integrates all available information sources and provides the operator with clear, consistent, explicit feedback for every control action,

Situational awareness means that the operator has visibility into the state of the system and the state of procedure execution. In the current LMC, a large set of displays provides the operator with visibility into the system. However, information important to the operator may not be easily accessible because there arc too many displays and none of them arc' user-definable. The LMC 0A team did not redesign the displays because the resources to tackle such a significantly large problem were not available. Rather, the LMC 0A prompts the user with the name of the display and the value to look for. Visibility into the state of procedure execution means that the operator knows the progress and status of procedure execut ion. Currentl y, since there dots not exist end-to-end procedural documentation, the operator depends on experience to determine the procedure. To determine the sta te of procedure execu t ion, the operator must interpret a large number of messages from the subsystem. However, through an extensive knowledge engineering effort, an end-to-end integrated procedure for VLBI was created and represented in a TDN. The TDN is a clear and intuitive way of representing the procedure to the user. Furthermore, through the color-coded, graphical display of the TDN, the operator car immediately determine exactly where he is in the procedure and the state of execution.

Temporal Dependency Network

One of the identified problems with the existing operational LMC is the lack of end-to-end procedural documentation. To perform a VLBI precalibration, the operator must refer to several operation manuals which describe individual subsystems or portions of the procedure. The operator must then manually create an integrated procedure. In some cases, operators create and use, as a reference, private "cheat sheets" which describe what needs to be done. The lack of a single source of documentation that describes the VLBI precalibration procedure results in inconsistent operations. Actual operations rely heavily on an individual operator's experience and expertise. To automate operations, we needed to create an integrated procedure for VLBI precalibration.

The approach to knowledge engineering was to first learn about the system through existing documentation, noting inconsistencies and missing information. The next Step was to discuss the procedure with the operators, engineers, technicians and scientists to get their viewpoints and to clear up inconsistencies as much as possible. This information led to our initial TDN. The TDN became the needed common language between our knowledge engineers and our knowledge sources. The LMC 0A knowledge engineering effort is the only known attempt, within the DSN, to produce a single, coherent and consistent baseline operational sequence for precalibration that merges the viewpoints of all the **users.**

The TDN, shown **in** Fig. 1, is a directed graph of interconnected blocks that represents an end-to-end operational sequence for VLBI. Sequential, parallel, and optional operation sequences are identified in the TDN. Each block in the TDN contains directives that are sent to the subsystems sequentially. Blocks have precedence constraints where the directives cannot be sent until all of its predecessor blocks' directives have successfully completed execution. Each block has associated precondition and postcondition constraints. These constraints define the state the system must be in before starting each block of directives, and after successful execution of those directives, respectively. Each block may also have temporal constraints which limit the start and completion of the directives to a specific time or time interval.

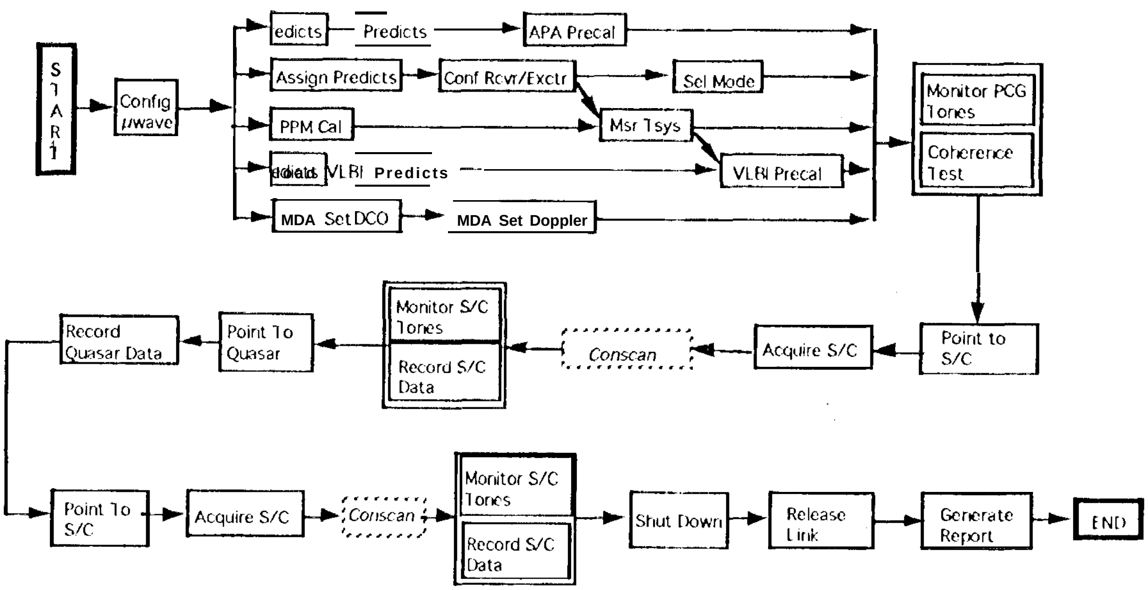

Fig. 1. A High Level VLBI Temporal Dependency Network.

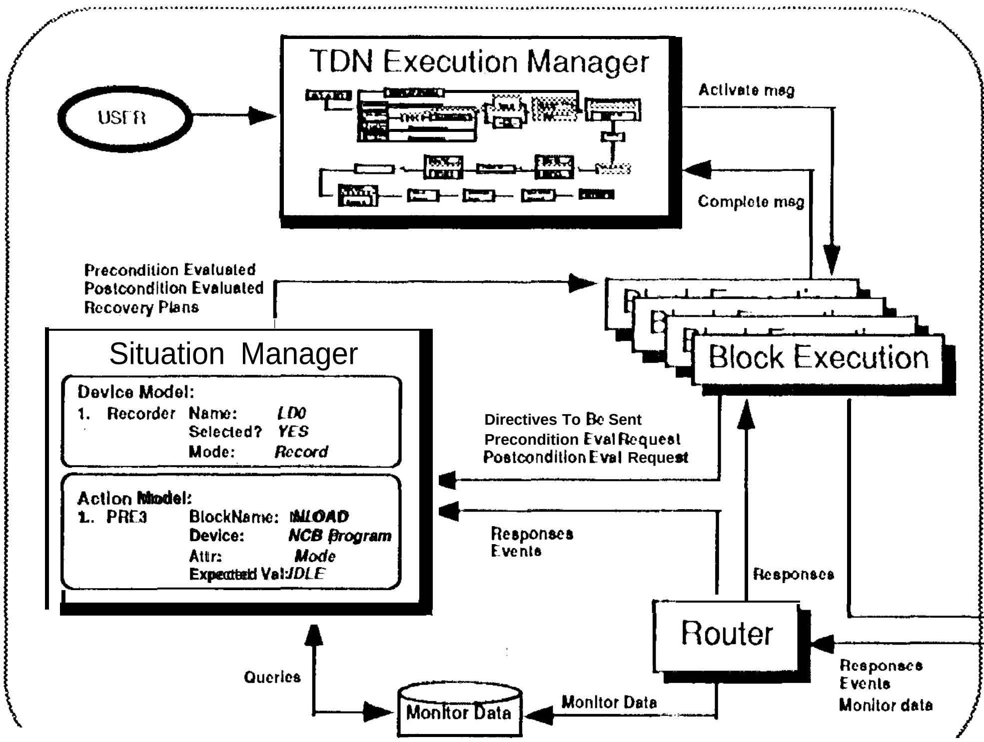

Fig. 2. The 1.MC OA architecture. '

Architecture

Our goal is to provide both closed loop control and closed loop communications for the operator. ~'here are two major modules in the 1.MC 0A: the TDN Execution Manager and the Situation Manager (SM). Other modules which will be discussed are the Block Execution module, Router, Monitor Data Handler and DSN Data Simulator. An overview of the architecture is presented in Fig. 2.

TDN Execution Manager and Block Execution Modules

The TDN EM **traverses** the TDN identifying blocks which are ready to execute. Blocks whose precedence constraints are satisfied are star-led. When a block is started, the user is asked to parameterize any unparameterized directives. The preconditons are then evaluated by the SM. A block's directives are sent only after the SM verifies that the preconditions are satisfied. After a directive is sent, a directive response must be received before the next directive in the block is sent to a subsystem. After t he last direct i ve is sent and its corresponding response is received, the block's postconditions are checked by the SM. If the postconditions are satisfied, the block of directives is considered completed.

Situation Manager

The Situation Manager provides situation management within the LMC 0A. It is an AI-based module that verifies correct execu tion of blocks of direct ives by checking postcond i t ion constraints. Problems are detected and simple recovery assistance is provided. To keep track of the system state, the SM keeps an internal model of all the monitorable hardware and software devices in the system. Each device represented in the model has attributes that reflect the state of the device. Each attribute has a pair of values: an *expected value* and an *actual value*. The expected value of an attribute, in the form of a postcondition, is set when a directive is sent to the subsystem. The actual value of an attribute is set when the subsystem sends messages noting state changes in the subsystem. Every directive sent to a subsystem is expected to cause certain known changes on the states of the devices in the subsystem. Each time a directive is sent, the expected values of the attributes in the device model arc updated.

Several data sources arc used to set the actual values of the device attributes: event notice messages, directive responses, monitor data and the operator, Event notice messages explicitly give the actual states of devices. Directive responses provide information on whether the directive has been received by the subsystem In some cases, they also provide progress and completion data. Monitor data arc blocks of status information that are sent periodically by the subsystems. Monitor data usually provide more information than event notice messages. Finally, operator input is requested in certain situations. The operator is provided a set of pre-defined monitor displays. The information in these displays is not always available from the monitor data blocks. These displays arc generated as bit-map displays at the subsystem level and arc unavailable to the LMC OA because of format and DSN operational restrictions. Therefore, for certain directives, the operator must obtain information from the displays and enter it into the LMC 0A. This information is used to set the actual value of an attribute in the SM internal device model. All four electronic data types provide information about the actual state of a device, but no explicit information about whether a directive was executed successfully. However, by using information about the expected and actual states of devices, the success of a directive can be inferred. With the SM maintaining its device models, information about the state of the system and the state of the procedure is always available to the operator.

Router, Monitor Data Handler and DSN Subsystem Simulator

in addition to the TDN execution, block execution and SM modules, there arc several other supporting modules. The Router is responsible for all communicant ions between the LMC OA and the DSN subsystems. 1 t receives and decodes input from the DSN subsystems and directs the input to either the TDN Execution Manager or the SM or both. It also formats the directives into communication packages that arc sent to the subsystems. The Monitor Data Handler receives Monitor Data blocks from the subsystems and stores them in the Monitor Data Database. Since access to the operational environment is limited, a DSN Subsystem Simulator was implemented to simulate the directive responses and event notice messages from the subsystems for testing.

User Interaction and Status Displays

One of the LMC 0A goals is to provide consistent interaction and meaningful displays to keep the user aware of what is transpiring in the system. The primary method of interaction is via menu or button selections with a mouse. occasionally, the operator may be asked to enter a value or response. 't'he primary interaction window is a b]ock-level display of the TDN which provides a high-level, end-to-end sequence of operations. A color bar in each block is used to show the status and progress of each block: a gray bar means the block is inactive, a green bar means the directives arc executing, a red bar means an anomaly has occurred and a blue bar means the directives have successfully completed. The portion of the color bar that is green is proportional to the number of executed directives in the block.

'1 'he operator can bring up a lower level display for each block that shows the state of the block, the state of each directive in the block (inactive, executing, paused, anomaly, etc.) and lists the preconditions and postconditions for each block, '1 'here are TDN-level controls to pause, resume and stop execution. Block-level and directive-level controls exist to pause, resume and skip execution. icons are used to show the user whether a block is paused or skipped.

SM anomaly messages that require a user response arc displayed in a separate window. A synopsis is displayed in a scrolling portion at the top of the window. By selecting a synopsis, the operator brings up a description of the anomaly in the bottom portion of the window. '1 'he operator can then enter the requested input or Select a default option.

'1 'hc scrolling event log lists all the input to and output from the LMC 0A system. A command window allows operator control outside of the TDN. Another display shows the end-of-pass report as it is being filled in by the LMC OA. in the existing 1 .MC system, the operator writes down the time at which certain direct ives were executed and their results. At the end of the pass, the operator wri tes a set of paper reports. The LMC OA internally logs the time, parameters and responses for each directive and reports are **automatically generated.**

Operational Scenario

A typical operations scenario using the 1 .MC 0A is as follows. The operator starts the I .MC 0A and selects a specific precalibration task such as VLBI. The corresponding TDN and knowledge bases are loaded and the TDN is graphically displa ycd. The operator enters the specific parameters for the next pass based on the support data. 1)irectives which require real-t ime data input, such as weather information, contain place holders for parameters. The operator can also tailor the TDN, skipping any unnecessary blocks, entering special directives, or establishing breakpoints, as needed. The process of preparing the TDN for a specific pass can be done at any time preceding the designated pass start time. At the start of the pass, the operator selects the start option, which is a single mouse click, to start execution of the TDN. The TDN can be paused or halted at any time during the process. The operator watches the execution of the TDN using the color coding in the graphical user interface.

At any time, the operator may bring up low level displays to see the execution state of the individual control directives. The low level display changes to reflect when each directive is sent and when it is verified completed. The SiM and TDN EM work in tandem to ensure that the control directives arc correlated with the monitor data and event messages. This correlated information is summarized and presented to the operator. If the SM detects a problem, it reports it to the user along with recovery suggestions. The user selects a recovery option which causes the TDN execution to continue or halts the execution of the TDN. A command window provides the operator with the ability to enter any control direct ives into the system. Another window provides a scrolling log of all incoming direct ives, d irective responses and event not ice messages. Additional windows provide a pass summary report and link status.

Results

The LMC OA prototype was tested at the Goldstone DSCC's 70-meter antenna while performing a VI .BI precalibration procedure. The LMC 0A was successfully tested over a three'-month period at Goldstone DSCC. The tests were in conjunction with maintenance and despite interruptions, the LMC 0A was used to perform a VI .BI precalibration in 27 minutes. 'l'his is 40% less than the standard time of 45 minutes. in addition, the 1 .MC 0A reduced operator-mtcrcd directives from over 100 to zero directi ves and 14 parameters.

Conclusion

Knowledge-based systems will play a major and enabling role in improving operability and capabilities of future ground systems at the DSN. "J 'he LMC 0A protot ypc demonstrates the feasibility and benefits of Al-based automation in DSN operations. The benefits of an operational, Semi-automated monitor and control system arc 1) reduction in precalibration t ime; 2) red uct ion in keyboard ent ry, which reduces occurrences of typographic errors; 3) enablement of parallel operations; and 4) increased operator efficiency via closed loop control. The LMC Operator Assistant demonstrates several operability improvements. 1 t provides the operator with mechanisms for closed loop control and situational awareness. It provides an end-to-end procedural representation for precalibration using a Temporal Dependency Network. It reduces the amount of keyboard entry required of the operator. Current efforts include extending the LMC OA to control multiple activities and demonstrating the LMC 0A at a 34 -meter experimental antenna complex.

Acknowledgments

The work described in this paper was carried Out by the Jet l'repulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. Past and present team members who have contributed to this version of the LMCOA arc Kristina Fayyad, Randall 1 lill, Juan Urista, Kathryn Sturdevant, Jay Wyatt, Crista Smyth and Sanguan Chow. The contributions of Pam Wolken, Terry Dow, Dave Girdner, Dan Kiewicz and the many operations personnel at the Goldstone Deep Space Communications Complex are gratefully acknowledged.

References

1. Cooper, 1 .ynne 1', "operations Automation Using Temporal Dependency Networks," Technology 2001, San Jose, CA, December s-5,1991.

2. Cooper, 1 .ynne P., Rajiv Desai and Elmain Martinez, "operator Assistant to Support Deep Space Network Link Monitor and Control," SOAR Symposium, 1 louston, TX, 1991.

3. Fayyad, Kristina E. and Lynne P. Cooper, "Representing Operations Procedures Using Temporal Dependency Networks," Space Ops '92, Pasadena, CA, November 199?

4. Hill, Randall W., Jr. and Lorrine F. Lee, "Sit uat ion Management in the Link Monitor and Control Operator Assistant (1 .MCOA)", SpaceOPS 92: Second International Symposium on Ground Data Systems for Space Mission Operations, Pasadena, CA, 1992.

5. 1 .ee, 1 .orrine F. and Randall W. I lill, Jr., "]'recess Control and Recovery in the Link **Monitor** and Cont rol Operator **Assist ant,"** **S p a c e** Operations, Applications and Research Symposium, Johnson Space Center, Houston, TX, August, 1992.

6. Urista, Juan. "Using MACH Threads t o Clint ml DSN Operational Sequences," Space Ops '92, Pasadena, CA, November 1992.

7. Wilkinson, Belinda, "Operability Engineering in the Deep Space Network," Space Ops '92, Pasadena, CA, November 1992.